

Emission spectrum of Sagittarius A* and the neutrino ball scenario

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ABSTRACT

The emission spectrum of the supermassive compact dark object at the Galactic center is calculated in the framework of standard thin accretion disk theory assuming that the compact object is a neutrino ball of $2.6 \times 10^6 M_\odot$ instead of a supermassive black hole. The neutrino ball scenario could explain the observed radio and infrared emission spectrum of the Galactic center for wavelengths between $\lambda = 0.3$ cm and $\lambda = 10^{-3}$ cm, if the neutrino mass and the accretion rate fulfil some constraints.

Subject headings: black hole physics — accretion disks — dark matter — elementary particles — Galaxy: center

1. Introduction

It is generally accepted that accretion onto compact objects is the most efficient mechanism of transforming gravitational potential energy into radiation (see, e.g., Frank et al. 1992). Sagittarius A* (Sgr A*) at the Galactic center is an unusual source of radiation which has remained a longstanding mystery. The dynamics of stars around the Galactic center (Eckart and Genzel 1996, 1997; Genzel et al. 1996, 1997 and Ghez et al. 1998) is usually interpreted as evidence for a supermassive black hole of mass $\sim 2.6 \times 10^6 M_\odot$ near Sgr A*. Observations of gas flows in the vicinity of Sgr A* reveal a mass accretion rate onto the central object of $\sim 10^{-4} M_\odot \text{yr}^{-1}$ (Melia 1992; Genzel et al. 1994). In standard thin accretion disk theory, with a reasonable efficiency of $\sim 10\%$, this accretion rate would correspond to a luminosity of $\sim 10^{42} \text{ erg s}^{-1}$. However, the actual luminosity observed is $\sim 10^{37} \text{ erg s}^{-1}$. Moreover, the spectrum is essentially flat in νL_ν from radio waves to X-rays, with the exception of a few bumps (Rogers et al. 1994, Menten et al. 1997, Predehl and Trümper 1994, Merc et al. 1996). Thus both the observed low luminosity and the spectral energy distribution differ very much from the spectrum that would be expected from a standard thin disk around a supermassive black hole. This discrepancy is known as the “blackness problem” of the Galactic center. Both the blackness of Sgr A* and its peculiar spectrum were the source of exhaustive debate in the recent past. Several models for the accretion and the emission spectrum of Sgr A* have been proposed. Melia (1994) modelled the spectrum of Sgr A* as synchrotron radiation emitted by thermal electrons, heated through the dissipation of magnetic energy, as a result of a Bondi-Hoyle accretion process fed by winds emanating from stars in the vicinity of Sgr A*. Optically thick synchrotron radiation emitted by a jet-disk system was also proposed as an explanation for the radiation of Sgr A* (Falcke, Mannheim and Biermann 1993; Falcke and Biermann 1996). Moreover, synchrotron radiation emitted by a quasi-monoenergetic ensemble of relativistic electrons (e.g. Beckert and Duschl 1997) has been put forward as a possible emission mechanism.

Probably the most sophisticated model that is consistent with the observed emission spectrum of Sgr A* from radio waves to γ rays is based on Advection Dominated Accretion Flows (ADAF) (Narayan et al.

1995, 1998; Mahadevan 1998; Manmoto et al. 1997). This model relies on the idea that most of the energy released by viscous dissipation is stored as thermal energy in the gas which is then advected to the center, thereby radiating off only a small fraction of the energy (Narayan and Yi 1995; Abramowicz et al. 1995). An essential ingredient of the ADAF models is that the compact dark object at the Galactic center is a *black hole*. In fact, the existence of an event horizon around the black hole is essential in order to ensure that whatever energy falls into the central object disappears without being re-radiated. This model also requires the protons to have a much higher temperature than the electrons, and the gas must therefore have a two-temperature structure. However, it has also been recently pointed out that ADAF models, as a solution of astrophysical accretion problems, should be treated with some caution, as their physical basis is somewhat uncertain (Bisnovatyi-Kogan and Lovelace 1999). Moreover, it is important to note that none of the above models, including ADAF, can predict the intrinsic shape and size of Sgr A* as observed at 7 mm (Lo et al. 1998). It is also worthwhile to note that the theoretical models for the emission of Sgr A* are unable to explain the VLBI observations of Sgr A*, revealing that the observed size follows a λ^2 dependence and the apparent source structure can be described by an elliptical Gaussian brightness distribution (Davies et al. 1976; Lo et al. 1985, 1993; Rogers et al. 1994; Krichbaum et al. 1998; Bower and Backer 1998).

A direct proof of the existence of a supermassive black hole would require the observation of objects that are moving at relativistic velocities at distances close to the Schwarzschild radius. However, the best current observations only probe the gravitational potential at radii 4×10^4 larger than the Schwarzschild radius of a black hole of mass $2.6 \times 10^6 M_\odot$ (Ghez et al. 1998). Thus there is no compelling direct evidence for the existence of a supermassive black hole at the Galactic center. It is therefore perhaps prudent not to focus too much on the black hole scenario as the only possible solution for the supermassive compact dark object at the Galactic center, without having explored alternative scenarios.

For instance, a compact dark stellar cluster could be an alternative to the black hole scenario. However, such clusters obey stringent stability criteria (see, e.g., Maoz 1995, 1998). A viable cluster must thus have both evaporation and collision time scales larger than the lifetime of our Galaxy, i.e. ~ 10 Gyr, and this is more likely to be fulfilled with a cluster of substellar objects. But, apart from a compact cluster of very low-mass black holes or brown dwarfs that is free of stability problems, the most attractive alternative to a dense and dark stellar cluster is a cluster of elementary weakly interacting particles.

In fact, such an alternative model for the supermassive compact dark object at the Galactic center has been developed (Viollier et al. 1992, 1993; Viollier 1994; Tsiklauri and Viollier 1996, 1998a,b, 1999; Bilić et al. 1998; Bilić and Viollier 1999a,b). Tsiklauri and Viollier (1998a) have argued that the Galactic center is made of nonbaryonic dark matter in the form of massive neutrinos condensed in a supermassive neutrino ball of $2.5 \times 10^6 M_\odot$ in which the degeneracy pressure of the neutrinos balances their self-gravity. A supermassive neutrino ball differs from a black hole of the same mass mainly by the shallow gravitational potential inside the neutrino ball. Such neutrino balls could have been formed in the early Universe during a first-order gravitational phase transition (Bilić and Viollier 1997, 1998, 1999a,b). It has been shown that the dark matter observed through stellar motion at the Galactic center (Ghez et al. 1998) is consistent with a supermassive neutrino ball of mass of 2.6×10^6 solar masses made of self-gravitating heavy neutrino matter (Munyanza, Tsiklauri and Viollier 1999). Moreover, it has been pointed out that tracking the orbit of the fast moving star S1 (Genzel et al. 1997) or S0-1 (Ghez et al. 1998), which is perhaps moving inside the neutrino ball, offers the possibility to distinguish, within a few years time, the supermassive black hole scenario from that of the neutrino ball, for the compact dark object at the Galactic center (Munyanza, Tsiklauri and Viollier 1998, 1999).

The purpose of this paper is to calculate the spectrum of the compact dark object at the Galactic

center based on standard thin accretion disk theory, assuming that this object is a supermassive neutrino ball rather than a black hole. We perform the calculation of the spectrum based on the most recent Ghez et al. 1998 data, including the error bars of the observations. While the observed motion of stars near the Galactic center yields a lower limit for the neutrino mass m_ν , the observed infrared drop of the emission spectrum of Sgr A* provides us with an upper limit for m_ν . A distance to the Galactic center of 8 kpc has been assumed throughout this paper. The outline of this paper is as follows: In section 2 we present the formalism used to calculate the spectrum in the neutrino ball scenario, and in section 3 we summarize and discuss our results.

2. Model and results

The basic equations which govern the structure of neutrino balls have been derived in a series of papers (Viollier et al. 1992, Viollier et al. 1993, Viollier 1994, Viollier and Tsiklauri 1996, Bilić and Viollier 1999a,b); we thus can be very brief here. Let us denote the dimensionless neutrino Fermi momentum by $X = p_\nu/(m_\nu c)$, where p_ν stands for the local Fermi momentum of the neutrinos of mass m_ν . The structure of the neutrino ball is governed by a system of two coupled differential equations (Bilić, Munyaneza and Viollier 1999), i.e.

$$\frac{dX}{dx} = -\frac{\mu}{x^2 X}, \quad (1)$$

$$\frac{d\mu}{dx} = \frac{8}{3} x^2 X^3, \quad (2)$$

subject to the boundary condition $X(0) = X_0$ and $\mu(0) = 0$. In Eqs. (1) and (2), x stands for the dimensionless radial coordinate $x = r/a_\nu$, μ denotes the dimensionless mass enclosed within a radius x , i.e. $\mu = m(r)/b_\nu$, and a_ν and b_ν are the length and mass scales, respectively, which can be expressed as

$$a_\nu = 2\sqrt{\frac{\pi}{g_\nu}} \left(\frac{M_{\text{Pl}}}{m_\nu}\right)^2 L_{\text{Pl}} = 2.88233 \times 10^{10} g_\nu^{-1/2} \left(\frac{17.2 \text{ keV}}{m_\nu c^2}\right)^2 \text{ km}, \quad (3)$$

$$b_\nu = 2\sqrt{\frac{\pi}{g_\nu}} \left(\frac{M_{\text{Pl}}}{m_\nu}\right)^2 M_{\text{Pl}} = 1.95197 \times 10^{10} M_\odot g_\nu^{-1/2} \left(\frac{17.2 \text{ keV}}{m_\nu c^2}\right)^2, \quad (4)$$

in terms of Planck's mass and length, $M_{\text{Pl}} = (\hbar c/G)^{1/2}$ and $L_{\text{Pl}} = (\hbar G/c^3)^{1/2}$, respectively. Here, g_ν is the spin degeneracy factor of the neutrinos and antineutrinos, i.e. $g_\nu = 2$ for Majorana and $g_\nu = 4$ for Dirac neutrinos and antineutrinos. By choosing the appropriate Fermi momentum and thus the neutrino density ($\sim X^3$) at the center of the neutrino ball, we can construct a solution corresponding to a neutrino ball of $2.6 \times 10^6 M_\odot$. In order to describe the compact dark object at the Galactic center as a neutrino ball, and constrain its physical parameters appropriately, it is worthwhile to use the most recent observational data by Ghez et al. 1998, who established that the mass enclosed within 0.015 pc at the Galactic center is $(2.6 \pm 0.2) \times 10^6 M_\odot$ solar masses. Following the analysis of Tsiklauri and Viollier 1998a, the constraints on the neutrino mass m_ν , in order to reproduce the observed matter distribution (Munyaneza, Tsiklauri & Viollier 1999), are for a $M = 2.4 \times 10^6 M_\odot$ neutrino ball $m_\nu \geq 20.81 \text{ keV } g_\nu^{-1/4}$, and the radius of the neutrino ball therefore obeys $R \leq 1.50 \times 10^{-2} \text{ pc}$. Using the value $M = 2.6 \times 10^6 M_\odot$, the bounds on the neutrino mass are $m_\nu \geq 18.93 \text{ keV } g_\nu^{-1/4}$, and the radius of the neutrino ball turns out to be $R \leq 1.88 \times 10^{-2} \text{ pc}$. Finally, for a $M = 2.8 \times 10^6 M_\odot$ neutrino ball, the range of the neutrino mass is $m_\nu \geq 18.21 \text{ keV } g_\nu^{-1/4}$, and the corresponding neutrino ball radius $R \leq 2.04 \times 10^{-2} \text{ pc}$. We can calculate

the angular velocity Ω of the matter falling onto the neutrino ball as

$$\Omega = \sqrt{\frac{Gm(r)}{r^3}} = \frac{c}{a_\nu} \sqrt{\frac{\mu}{x^3}}, \quad (5)$$

where G is Newton's gravitational constant. The total mass of the neutrino ball is $M = m(R)$. In the case of a black hole, we have $M = m(r)$ already for radii much larger than the Schwarzschild radius. In Fig. 1, we plot the angular velocity as a function of the distance from the center for a neutrino ball of mass $M = 2.6 \times 10^6 M_\odot$ and a neutrino mass $m_\nu g_\nu^{1/4} c^2 = 18.93$ keV. The angular velocity corresponding to a black hole of the same mass is also shown for comparison. Close to the center of the neutrino ball, $\Omega(r)$ is nearly constant, and the mass enclosed within a radius r therefore scales as r^3 .

In the standard theory of steady and geometrically thin accretion disks, the power liberated in the disk per unit area is given by (Perry & Williams 1993; Frank et al. 1992)

$$D(r) = -\frac{\dot{M}\Omega(r)\Omega'(r)r}{4\pi} \left[1 - \left(\frac{R_i}{r} \right)^2 \left(\frac{\Omega_i}{\Omega} \right) \right]. \quad (6)$$

Here R_i is the inner radius of the disk and Ω_i defines the angular velocity at the radius where $\Omega(r)$ has a maximum, i.e. $\Omega_i = \Omega(R_i)$. The prime on the function $\Omega(r)$ denotes the derivative with respect to r . The accretion rate \dot{M} is parametrized as

$$\dot{M} = \dot{m} \dot{M}_{\text{Edd}}, \quad (7)$$

where $\dot{M}_{\text{Edd}} = 2.21 \times 10^{-8} M \text{ yr}^{-1}$ denotes the Eddington limit accretion rate. The maximal and minimal accretion rate allowed by the observations are $\dot{m} = 4 \times 10^{-3}$ and 10^{-4} (Narayan et al. 1998), respectively. The outer radius of the disk has been taken as 10^5 Schwarzschild radii, since for larger radii, the disk is unstable against self-gravity (Narayan et al. 1998). We now use Stefan-Boltzmann's law, assuming that the gravitational binding energy is immediately radiated away

$$D(r) = \sigma T_{\text{eff}}^4(r), \quad (8)$$

where σ is the Stefan-Boltzmann constant. The effective temperature T_{eff} can be easily derived using Eqs. (5), (6) and (8) yielding

$$\begin{aligned} T_{\text{eff}}(r) &= \left(\frac{\dot{M}_{\text{Edd}} G}{8\pi\sigma} \right)^{1/4} \frac{b_\nu^{1/4}}{a_\nu^{3/4}} \dot{m}^{1/4} \left(\frac{3\mu - \mu'x}{x^3} \right)^{1/4} \left[1 - \left(\frac{x_i}{x} \right)^2 \frac{\Omega_i}{\Omega} \right]^{1/4} \\ &= T_0 \dot{m}^{1/4} \left(\frac{3\mu - \mu'x}{x^3} \right)^{1/4} \left[1 - \left(\frac{x_i}{x} \right)^2 \frac{\Omega_i}{\Omega} \right]^{1/4}, \end{aligned} \quad (9)$$

where the constant T_0 is given by

$$T_0 = \left(\frac{\dot{M}_{\text{Edd}} G}{8\pi\sigma} \right)^{1/4} \frac{b_\nu^{1/4}}{a_\nu^{3/4}}. \quad (10)$$

Once the temperature distribution in the disk is specified, one can find its luminosity at a frequency ν using

$$\frac{dL_\nu}{dr} = \frac{16\pi^2 h \nu^3 \cos(i)}{c^2} \frac{r}{\exp\left(\frac{h\nu}{k_B T_{\text{eff}}}\right) - 1}, \quad (11)$$

with $L_\nu(x_i) = 0$. In Eq. (11), h and k_B are Planck's and Boltzmann's constants, respectively, and the disk inclination angle i is assumed to be 60° as in Narayan et al. (1998). Picking up a particular value for ν ,

we may integrate Eq. (11) numerically, taking the inner radius of the disk to be determined by $\Omega'(r) = 0$. However, the inner radius of the accreting disk can be chosen to be zero, as the inner region, where $\Omega(r)$ is nearly constant, does not contribute to the emission spectrum anyway. It is worthwhile to note, that in the case of a neutrino ball, there is no last stable orbit, in contrast to the black hole case, where the inner radius of the disk is taken to be three Schwarzschild radii. The results of this integration are shown in Figure 2, where the spectrum emitted in the case of accretion onto a black hole (dotted lines) of $M = 2.6 \times 10^6 M_\odot$ is shown as well. Here, accretion rates of $\dot{m} = 10^{-3}$, 10^{-4} and 10^{-9} have been assumed for both scenarios. Also shown in this plot are the most up-to-date observations of the emission spectrum of the Galactic center (Narayan et al. 1998). The arrows represent upper limits, and the box at a frequency $\sim 10^{17}$ Hz stands for the uncertainty in the observed X-ray flux. The open and filled squares represent various flux measurements and upper limits for Sgr A*. The open squares stand for the low angular resolution points while the filled squares represent the data points with best resolution. The observed spectrum rises at radio and submillimeter frequencies of $\nu \simeq 10^9$ to 10^{12} Hz, where most of the emission occurs, and it has a sharp drop in the infrared. The X-ray observations consist of a possible detection at soft X-ray energies, and firm upper limits in the hard X-rays. As seen in Fig. 2, the neutrino ball model reproduces the observed spectrum from the radio ($\lambda = 0.3$ cm) to the near infrared band ($\lambda = 10^{-3}$ cm) very well. Thus, as our model fulfils two of the most stringent conditions, i.e. it is consistent with the mass distribution (Genzel et al. 1997, Ghez et al. 1998) and the bulk part of the emitted spectrum, we conclude that the neutrino ball scenario is not in contradiction with most of the currently available observational data. As we see from Fig. 2 and also as pointed out by Narayan et al. 1998, the curves corresponding to the black hole (lines 4, 5 and 6) provide a poor fit to the observational data. A starving black hole, with an accretion rate of $\dot{m} = 10^{-9}$ (line 6 in Fig. 2) would not fit the observed spectrum either. This is in fact the main reason why standard accretion disk theory was abandoned as a possible candidate for the description of the Sgr A* spectrum (Narayan et al. 1995). Figure 3 shows the temperature of the disk as a function of the radius, for an accretion rate of $\dot{m} = 10^{-3}$ in both scenarios.

The spectrum presented in Fig. 2 corresponds to a neutrino ball or black hole of $M = 2.6 \times 10^6 M_\odot$. To draw definite conclusions about the emission spectrum of a neutrino ball, it is necessary to investigate the dependence of the spectrum on i) the mass of the neutrino ball; ii) the neutrino mass m_ν , both with the ranges allowed by the Ghez et al. 1998 data. In Fig. 4, we present the emission spectrum for a variety of neutrino ball masses, i.e. $M = 2.4, 2.6, 2.8 \times 10^6 M_\odot$. From this plot, we conclude that, within the uncertainties, the mass of the neutrino ball has no significant effect on the spectrum of the neutrino ball. In Fig. 5, we plot the spectrum as a function of the neutrino mass for different accretion rates. The top panel represents the spectrum for an accretion rate of $\dot{m} = 10^{-4}$ while the lower describes an accretion rate of $\dot{m} = 10^{-3}$. The neutrino mass m_ν has been varied as shown on the plot. As the observed emission spectrum has a sharp drop in the infrared region, we require the theoretical spectrum not to extend to frequencies beyond the innermost data points of the infrared drop of the observed spectrum, yielding an upper bound for the neutrino mass. For each value of the accretion rate, an upper bound for the neutrino mass is established using this condition. This is reflected in Fig. 6, where we plot the neutrino mass $m_\nu c^2$ as a function of the accretion rate \dot{m} . The vertical arrows pointing down show the inferred upper limits of the neutrino mass for each accretion rate. Thus for $\dot{m} = 10^{-4}$, the upper limit is $m_\nu c^2 g_\nu^{1/4} \leq 29.73$ keV; for $\dot{m} = 8 \times 10^{-4}$, the range of the neutrino mass is $m_\nu c^2 g_\nu^{1/4} \leq 19.74$ keV; for $\dot{m} = 10^{-3}$, the neutrino mass is constrained by $m_\nu c^2 g_\nu^{1/4} \leq 18.93$ keV; and finally for $\dot{m} = 4 \times 10^{-3}$, the upper limit is found to be $m_\nu c^2 g_\nu^{1/4} \leq 17.24$ keV. The horizontal line shows the lower limit on the neutrino mass obtained by fitting the mass distribution of the neutrino ball with the currently best observational data (Ghez et al. 1998). Combining both upper and lower limits for the neutrino mass, we arrive at the following constraints for the

neutrino mass

$$18.93 \text{ keV} \leq m_\nu c^2 g_\nu^{1/4} \leq 29.73 \text{ keV for } \dot{m} = 10^{-4}, \quad (12)$$

$$18.93 \text{ keV} \leq m_\nu c^2 g_\nu^{1/4} \leq 19.74 \text{ keV for } \dot{m} = 8 \times 10^{-4}. \quad (13)$$

From Fig. 6, we may conclude: i) In order to be consistent with the observational Ghez et al. 1998 data, the accretion rate \dot{m} onto the neutrino ball should be less than $\sim 10^{-3}$, implying an accretion rate \dot{M} onto the neutrino ball that is less than $\sim 5.7 \times 10^{-5} M_\odot \text{yr}^{-1}$; ii) The neutrino mass range is bounded from below by the Galactic kinematics and also bounded from above by the spectrum. The range of allowed values of the neutrino mass narrows as the accretion rate increases, vanishing at $\dot{m} \geq 10^{-3}$.

3. Summary and discussion

We have studied the emission spectrum of Sgr A* assuming that it is a neutrino ball of mass $M = (2.6 \pm 0.2) \times 10^6 M_\odot$ with a size of a few tens of light days. We have shown that, in this case, the theoretical spectrum, calculated in standard thin accretion disk theory, fits the observations in the radio and infrared region of the spectrum much better in the neutrino ball than in the black hole scenario, as seen from Fig. 2. This is because, in the neutrino ball scenario, the accreting matter experiences a much shallower gravitational potential than in the case of a black hole with the same mass, and therefore less viscous torque will be exerted. Here, we note that the emitting region for this part of the spectrum is of the order of the size of the neutrino ball, i.e. a few tens of light days. We have shown that the error bars in the mass of the neutrino ball have practically no significant effect on the spectrum of Sgr A*. By assuming that the emission spectrum cannot extend beyond the observed innermost data points of the infrared drop of the Sgr A* spectrum, we have established that the range of possible values of the neutrino mass narrows as the accretion rate \dot{m} increases. We have also shown that an accretion rate of more than $\dot{M} > 5.7 \times 10^{-5} M_\odot \text{yr}^{-1}$ would render the allowed range of neutrino masses inconsistent with the lower limit obtained from the observational data based on the kinematics of stars.

The thin accretion disk neutrino ball scenario alone can, of course, neither explain the lower part of the radio spectrum, i.e. $\nu \lesssim 2 \times 10^{11} \text{ Hz}$, nor can it explain a possible spectrum for $\nu \gtrsim 10^{14} \text{ Hz}$. The latter is a consequence of the fact that the escape velocity from the center of the neutrino ball of $2.6 \times 10^6 M_\odot$ is only about 1700 km/s. In order to get X-rays, the particles need to reach a sizable fraction of the velocity of light, which is impossible in the pure neutrino ball scenario. However, as the heavy neutrinos presumably decay radiatively ($\nu_\tau \rightarrow \nu_\mu + \gamma$ or $\nu_\tau \rightarrow \nu_e + \gamma$) with a lifetime of $\gtrsim 10^{18} \text{ yr}$ (assuming Dirac neutrinos and the current limits for the mixing angles), there will be some X-ray emission of the order of $\lesssim 10^{34} \text{ erg s}^{-1}$ at an energy of $m_\nu c^2/2$, which could be presumably detected by the CHANDRA X-ray satellite. Moreover, if both neutrinos and antineutrinos are present in the neutrino ball, annihilation ($\nu_\tau + \bar{\nu}_\tau \rightarrow \gamma + \gamma$) will also contribute to the X-ray spectrum at an energy $m_\nu c^2$, concentrated at the center of the neutrino ball, albeit with a much smaller luminosity (Viollier 1994). Furthermore, it is worthwhile to speculate that a neutron star at the Galactic center, surrounded by a neutrino halo of $M = 2.6 \times 10^6 M_\odot$, might explain the observed spectrum of Sgr A*. A similar idea was proposed long ago by Reynolds and McKnee 1980, who suggested that the radio emission of Sgr A* could be due to an otherwise unobservable radio pulsar. However, as the accretion rate onto the neutrino ball is of the order of $\dot{M} = 10^{-5} M_\odot \text{yr}^{-1}$, i.e. three orders of magnitude larger than the Eddington accretion rate of $\sim 10^{-8} M_\odot \text{yr}^{-1}$ onto a neutron star, much of the baryonic matter falling towards this neutron star will have to be expelled before reaching the neutron star surface.

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REFERENCES

- Abramowicz, M. A. , Chen, X., Kato, S., Lasota, J. P., and Regev, O. 1995, ApJ., 438, L37
- Beckert, T. and Duschl, W. J. 1997, A&A, 328,95
- Bilić, N., Munyaneza, F., and Viollier, R.D. 1999, Phys. Rev. D59, 024003
- Bilić, N., Tsiklauri, D., and Viollier, R. D., 1998, Prog. Part. Nucl. Phys. 40, 17
- Bilić, N. and Viollier, R. D. 1997, Phys. Lett. B408, 75
- Bilić, N. and Viollier, R. D. 1998, Nucl. Phys. (Proc. Suppl.) B66,256
- Bilić, N. and Viollier, R. D. 1999a, Gen. Rel. Grav. to be published , gr-qc/9706019
- Bilić, N. and Viollier, R. D. 1999b, Eur. Phys. J. C , to be published, hep-ph/9809563
- Bisnovatyi-Kogan, G. S. and Lovelace, R. V. E. astro-ph/9902344
- Bower , G. C. and Backer, D. C. 1998, ApJ, 496,L97
- Davies, R. D., Walsh , D., and Booth , R. S., 1976, MNRAS,177,319
- Eckart, A. and Genzel, R. 1996, Nature, 383,415
- Eckart, A. and Genzel, R. 1997, MNRAS, 284, 576
- Falcke, H., Mannheim, K., and Biermann, P. 1993, A & A, 278, L1
- Falcke, H. and Biermann, P. I., 1996, A & A 308, 321
- Frank J., King, A., and Raine, D. 1992, Accretion Power in Astrophysics (Cambridge Univ. Press, Cambridge)
- Genzel, R., Eckart, A., Ott, T., and Eisenhauer, F. 1997, MNRAS, 291, 219
- Genzel, R., Hollenbach, D. J., and Townes, C. H. 1994, Rep. Prog. Phys. 57, 417
- Genzel, R., Thatte, N., Krabbe, A., Kroker, H., and Tacconi-Garmann, L.E. 1996, ApJ, 472, 153
- Ghez, A.M., Klein, B.L., Morris, M., and Becklin, E.E. 1998, ApJ , 509, 678
- Krichbaum, T. P. *et al.* 1998, A&A, 335, L106
- Lo , K. Y. *et al.* , 1985, Nature, 315,124
- Lo, K. Y *et al.* , 1993, Nature,362, 38
- Lo, K. Y., Zhi-Qiang Shen, Zhao Jun-Hui, and Ho, T. P. astro-ph/9811375
- Mahadevan , R. , 1998, Nature , 394,651
- Manmoto, T., Mineshige, S. , and Kusunose, M. 1997, ApJ, 489, 791
- Maoz, E. 1995, ApJ, 447, L91
- Maoz, E. 1998, ApJ, 497, L181

- Melia , F., 1992, ApJL, 387, L25
- Melia, F. 1994, ApJ., 426, 577
- Menten, K. M., Reid, M. J. , Eckart, A., and Genzel, R. 1997, ApJ 475, L111
- Merc, M. *et al.* 1996, Astron. Astrophys. Suppl., 120, 465
- Munyanaza, F. , Tsiklauri, D., and Viollier, R. D. 1998, ApJL, 509, L105
- Munyanaza, F., Tsiklauri, D. , and Viollier, R. D. 1999, ApJ, 526, to be published, astro-ph/9903342
- Narayan, R. and Yi, I. ApJ 1995, 452 , 710
- Narayan, R., Yi, I., and Mahadevan, R., 1995, Nature, 374, 623
- Narayan, R., Mahadevan, R., Grindlay, J. E., Popham, R. G. , and Gammie, C. 1998, ApJ, 492, 554
- Predehl, P. and Trümper, J. 1994, A&A, 290, L29
- Perry, J. J. and Williams, R. 1993, MNRAS, 260, 437
- Reynolds, S. P. and McKee, C. F., ApJ, 1980, 239, 893
- Rogers, A. E. E., Doeleman, S., Wright, M. C. H., Bower, G. C., Backer, D. C., Padin, S., Philips, J. A. , Emerson, D. T. , Greenhill L., Moran, J. M., and Kellermann, K. I. 1994, ApJ, 434, L59
- Tsiklauri, D. and Viollier, R. D. 1996, MNRAS, 282,1299
- Tsiklauri, D. and Viollier, R.D. 1998a, ApJ, 500, 591
- Tsiklauri, D. and Viollier, R. D. 1998b, ApJ, 501, 486
- Tsiklauri, D. and Viollier, R.D. 1999, Astropart. Phys. to be published, astro-ph/9805272
- Viollier, R. D., Leimgruber, F. R., and Trautmann, D. 1992, Phys. Lett., B297, 132
- Viollier, R. D., Trautmann, D., and Tupper, G. B. 1993, Phys. Lett., B306, 79
- Viollier, R. D. 1994, Prog. Part. Nucl. Phys., 32, 51

Figure captions:

Fig 1: The angular velocity as a function of the distance from the center for the neutrino ball and the black hole scenarios. The neutrino ball and the black hole have the same mass $M = 2.6 \times 10^6 M_\odot$.

Fig 2: The spectrum of Sgr A* in both scenarios for various accretion rates. The continuous curves (lines 1,2,3) correspond to a disk immersed in the potential of a neutrino ball while the dashed lines (lines 4,5,6) correspond to a disk around a black hole. Lines 1 and 4 stand for an accretion rate of $\dot{m} = 10^{-3}$, while lines 2 and 5 correspond to an accretion rate of $\dot{m} = 10^{-4}$. Finally, an accretion rate of $\dot{m} = 10^{-9}$ for a starving disk is represented by the lines 3 and 6. The observed data points, taken from Narayan et al. 1998, have been included in this plot. The arrows denote upper bounds. The filled squares show the data with high resolution while the open circles represent the data with less resolution.

Fig. 3: The temperature of the disk as a function of the distance from the center for both scenarios. The accretion rate is $\dot{m} = 10^{-3}$.

Fig. 4: The Sgr A* emission spectrum for neutrino ball masses $M = 2.4, 2.6$ and 2.8×10^6 solar masses. The thick lines (1,3,5) correspond to an accretion rate of $\dot{m} = 10^{-3}$ while the thin lines (2,4,6) are drawn for $\dot{m} = 10^{-4}$. The mass of the neutrino ball does not have a significant effect on the spectrum of Sgr A*.

Fig. 5: The Sgr A* emission spectrum for various neutrino masses m_ν . An upper limit for the neutrino mass is inferred by requiring that the theoretical spectrum cannot go beyond the innermost points of the infrared drop of the observed spectrum. The top panel represents the spectrum for $\dot{m} = 10^{-4}$ while the lower describes an accretion rate of $\dot{m} = 10^{-3}$.

Fig. 6: The neutrino mass m_ν as a function of the accretion rate \dot{m} for $g_\nu = 2$. The horizontal line, with arrows pointing up, shows the lower limit of the neutrino mass, as obtained from the dynamics of stars. The arrows pointing down denote the upper limit, determined from the drop of the spectrum in the infrared region. The range of the neutrino mass narrows as the accretion rate \dot{m} increases. For $\dot{m} > 10^{-3}$, the upper limit on the neutrino mass becomes inconsistent with the lower limit from the dynamics of stars.